# Gyrokinetic simulation of fast L-H bifurcation dynamics in a realistic diverted tokamak edge geometry

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*Computing resources provided by OLCF at ORNL

# Different experimental observations in L-H transition

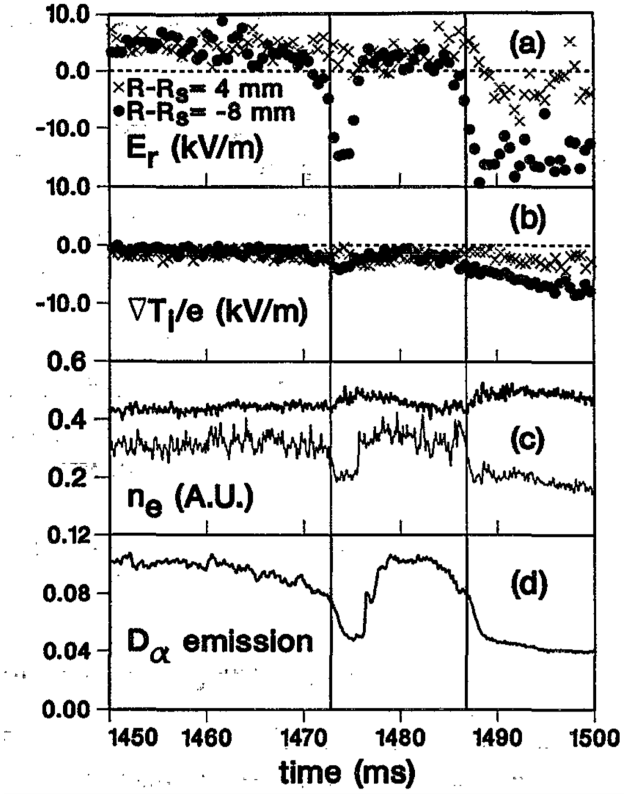
Two different types of experimental observations for the role of the sheared-ExB flow ($V'_{ExB}$) in edge-turbulence bifurcation:

1. Turbulence generated zonal $V'_{ExB}$: *Reynolds stress*
   - Yan et al., IAEA16 & PRL14; Schmitz, IAEA16; Tynan, NF13; Cziegler PPCF 14, and others]
2. Neoclassically generated $V'_{ExB}$: *X-point orbit-loss* [Chang et al, PoP02] or dP/dr
   - Kobayashi et al., PRL13, and others (X-point orbit-loss)
   - Cavedon, NF17 (Neoclassical dP/dr)
   - NSTX finds that $P_{L\text{-}H}$ is strongly correlated with orbit-loss $V'_{ExB}$ [Kaye, NF11; Battaglia, NF13]

# 1. Turbulent zonal $V'_{ExB}$ & L-H bifurcation in experiment

- $F_{\theta,Reynolds} = -d\langle\delta V_r \delta V_\theta\rangle/dr$
- Became basis for the predator-prey model [Kim-Diamond, PRL03, and others]
- When the turbulent Reynolds energy extraction ($\int dt\, F_{\theta,Reynolds}$) exceeds the turbulent kinetic energy, the turbulence quenching can occur.

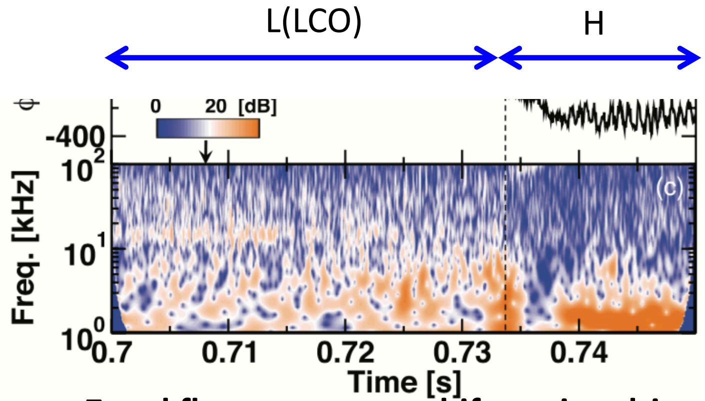
- **Unanswered questions if Reynolds stress is solely responsible for L-H**
  - Right after the turbulence quenching, what is supporting the strong $V'_{ExB}$?
    - Several experiments report that a strong $\nabla p$ develops only well after a fast bifurcation event [Moyer et al., PoP1995; and others]
  - What breaks the symmetry in the $F_{Reynolds}$, thus the Reynolds-driven $V'_{ExB}$, direction?
  - Why some machines do not see much Reynolds work?




[Moyer et al., PoP1995]

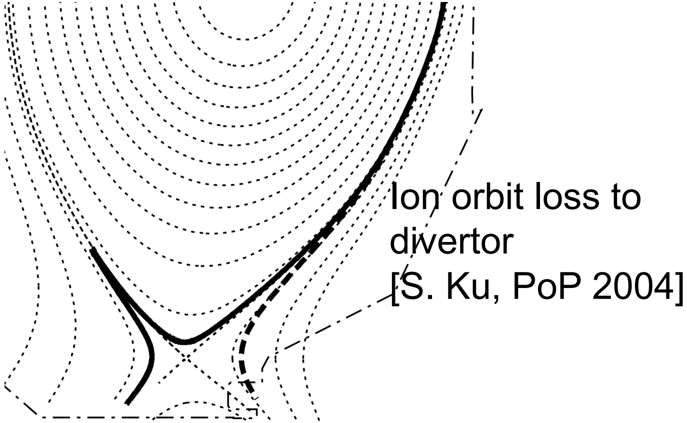
# 2. Neoclassically generated $V'_{ExB}$ & L-H bifurcation in experiment, w/o seeing much Reynolds work

- $V'_{ExB}$ is driven by $\nabla p$ [Cavedon et al., NF2017, ASDEX-U]
- Orbit-loss-driven $V'_{ExB}$ [Kobayashi et al., PRL2013, and others]
- NSTX found $P_{L\text{-}H}$ is strongly correlated with orbit-loss $V'_{ExB}$ [Kaye, NF2011; Battaglia, NF2013]



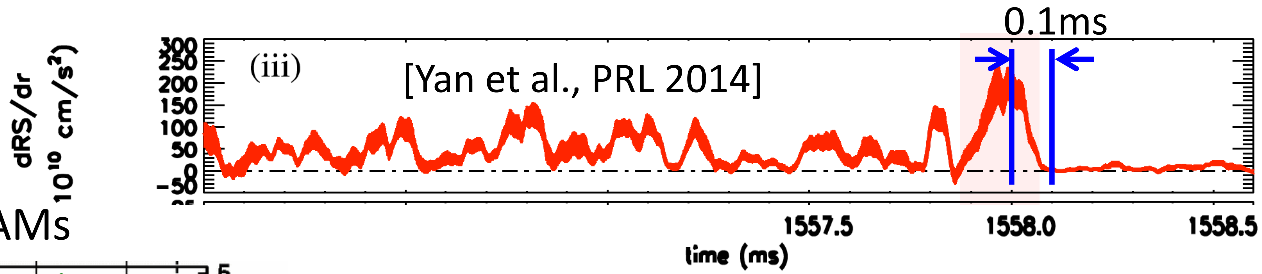

**Zonal flow not seen as bifurcation driver**
[Kobayashi., NF 2017]

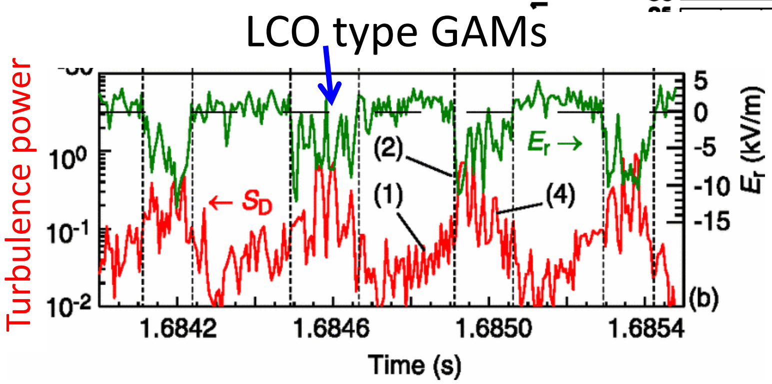
- Could it be possible that the Reynolds stress and orbit loss mechanism work together, with one stronger than the other depending upon the plasma/geometry condition?
- Could the combined Reynolds and X-loss physics provide the missing puzzle pieces in L-H transition physics?



# Experimental observations of L-H bifurcation time scale, GAM, and LCO

- When the heating power is very close to $P_{LH}$, the bifurcation is observed to be slow with many limit cycle oscillations (I-phase) [Schmitz et al. PRL12 and others]
- When the heating power is > $P_{LH}$, the bifurcation is (forced to be) **fast (< 0.1 ms)** with an abbreviated I-phase [Yan PRL14, and others]
- **GAMs and Limit cycle oscillations** observed as L-mode approaches the L-H bifurcation [Conway et al., PRL11]




LCO-type GAMs can be part of the bifurcation physics.

[Conway, PRL 2011]

# Why has a gyrokinetic L-H study not been done previously?

- Scale-inseparable, nonlocal multiscale in space and time
  - Turbulence
  - Neoclassical with ion orbit loss
  - Neutral particles with ionization and charge exchange
  - Radial turbulence correlation width ~ plasma gradient scale length ~ orbit width ~ ExB shearing width ~ neutral penetration length
- Magnetic separatrix ($q=\infty$), which interfaces two different magnetic topologies
- Large amplitude nonlinear turbulence: $\delta n/n > 10\%$
- Non-Maxwellian plasma
  - Requires fully nonlinear and conserving Collisions
- Long core-edge radial energy balance time ~core-edge confinement time >> GK time

→ Total-f simulation with ~100X more number of marker particles than delta-f simulation in the complex edge geometry: XGC.

→ We thought it would require exascale computer, non-existent yet.

# A new strategy for GK simulation of L-H transition

- If we were to establish a global transport-equilibrium in an L-mode plasma, move toward the bifurcation by quasistatically increasing $P_{heat}$, go through the bifurcation, and build up pedestal, we would not have enough compute resources to study the transition.

  → Requires >100X faster computer than Titan at ORNL.

- **A new strategy** to make the transition physics study possible on present HPCs:
- Bifurcation may not be a global transport-equilibrium phenomenon
  - But a localized phenomenon at edge
  - May not need to wait until GAMs die out
- Study only the edge bifurcation itself, as soon as the L-mode edge turbulence is established.
  - Force the bifurcation by having $P_{edge} \gg P_{LH}$
  - Experimentally, a forced L-H bifurcation action could be completed in <0.1ms (Yan-McKee, PRL2014, and others).
  - Take advantage of the fast establishment of edge physics
- Low beta electrostatic simulation

# In the core plasma, f evolves slowly

For simplicity, let's use the drift kinetic equation for this argument

$$\frac{\partial f}{\partial t} + (v_{||} + v_d) \cdot \nabla f + \frac{e}{m} E_{||} v_{||} \frac{\partial f}{\partial w} = C(f, f) + \mathrm{Sources/Sinks}$$

**In a near-thermal equilibrium,**

Let $f = f_0 + \delta f$ , with $\frac{\delta f}{f_0} = O(\rho_* \equiv \frac{\rho}{a}), \rho_* \ll 1, \frac{v_d}{v_{||}} = O(\rho_*), \frac{E_{||}}{m} = O(\rho_* \text{ or } \rho_*^2)$

*O(δ⁰):* $v_{||} \cdot \nabla f_0 = C(f_0, f_0) \rightarrow f_0 = f_M$ : H-theorem

*O(δ¹):* $\frac{\partial \delta f}{\partial t} = -v_{||} \cdot \nabla \delta f - v_d \cdot \nabla f_0 - \frac{e}{m} E_{||} v_{||} \frac{\partial f_0}{\partial w} + C(\delta f)$

- Perturbative kinetic theories then yield transport coefficients =$O(\rho_*^{\,2})$
- $f = f_0 + \delta f$ *evolves on a slow time scale* $O(\rho_*^{1}\omega_{bi})^{-1}$ *~ ms: core GK time scale*

→ ***δf*** **-GK simulation is cheaper per physics time (small computers), but equilibrates on a slow time scale** $O(\rho_* \omega_{bi})^{-1}$ *~ ms.*

# In edge plasma, f evolves fast

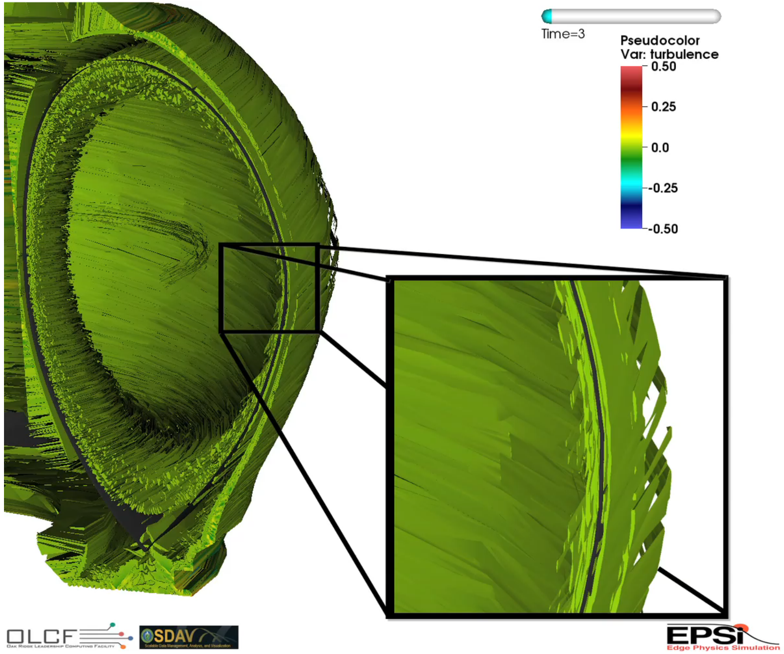
- Ion radial orbit excursion width ~ pedestal width & scrape-off layer width
- Orbit loss from $\psi_N<1$ and parallel particle loss to divertor

– **All terms can be large: ~ either $O(\omega_{bi})$ or $O(\nu_C)$**

  - $\mathbf{v}_{||}\cdot\nabla f \sim \mathbf{v}_d\cdot\nabla f \sim C(f,f) \sim eE_{||}v_{||}/m\,\partial f/\partial w \sim O(\omega_{bi})$ ~ 0.05 ms in DIII-D
  - *f* equilibrates very fast:

$$\frac{\partial f}{\partial t} = -\left(v_{||} + v_d\right)\cdot\nabla f - \frac{e}{m}E_{||}v_{||}\frac{\partial f}{\partial w} + C(f,f) + S$$

– **Fast-evolving nonthermal kinetic system: expensive per physics time → extreme scale computing. However, a short time simulation (~0.1ms) can yield meaningful physics.**



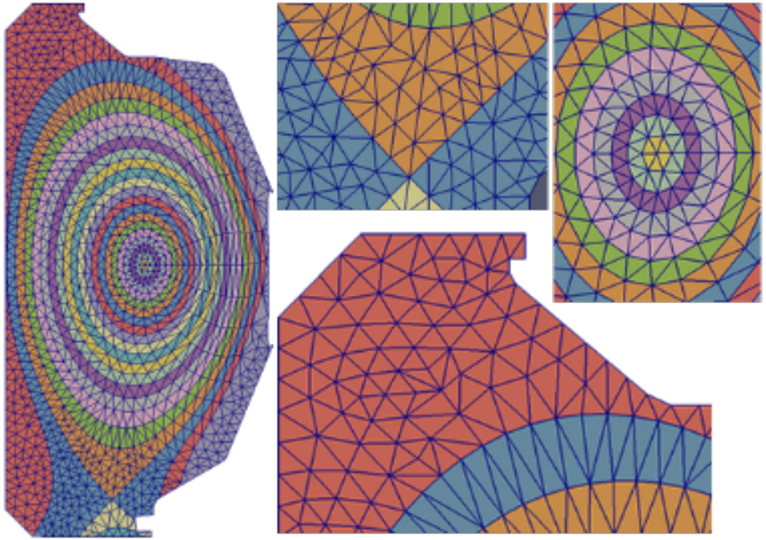

The edge turbulence around the separatrix saturated while the core turbulence has not built up.

# XGC gyrokinetic codes (V&V summary at epsi.pppl.gov)

- XGC1: X-point Gyrokinetic Code 1
- Gyrokinetic ions and electrons
- Lagrangian PIC + Eulerian 5D grid
- Steep electrostatic pedestal ordering [Hahm PoP 2009]
- Heat and momentum source in core
- Monte Carlo neutrals with wall recycling
- Fully nonlinear Fokker-Planck Coulomb collision operation
- Logical wall-sheath
- Unstructured triangular mesh

**Capabilities**

- ES with GK ions + drift-kinetic electrons **[C.S. Chang PP11.72, D.P. Stotler TP11.85, I.K. Charidakos TP11.84]**
- GK ions + fluid electrons **[R. Hager TP11.97]**
- EM with fully implicit drift-kinetic electrons (partially verified)
- Gyrokinetic electrons for ETG **[J. Chowdhury PP11.51]**
- RMP and stellarator **[J. Kwon TP11.95, T. Moritaka JP11.147, M. Cole CP11.70]**
- Multiscale coupling **[J. Dominski TP11.111, B. Sturdevant JP11.146]**



Full-f + Neutral particles + Unstructured triangular grid

→ Expensive to simulate

→ Requires extreme scale HPCs

# For the present L-H bifurcation study, we have performed a low-beta electrostatic edge simulation using XGC1

Plasma input condition

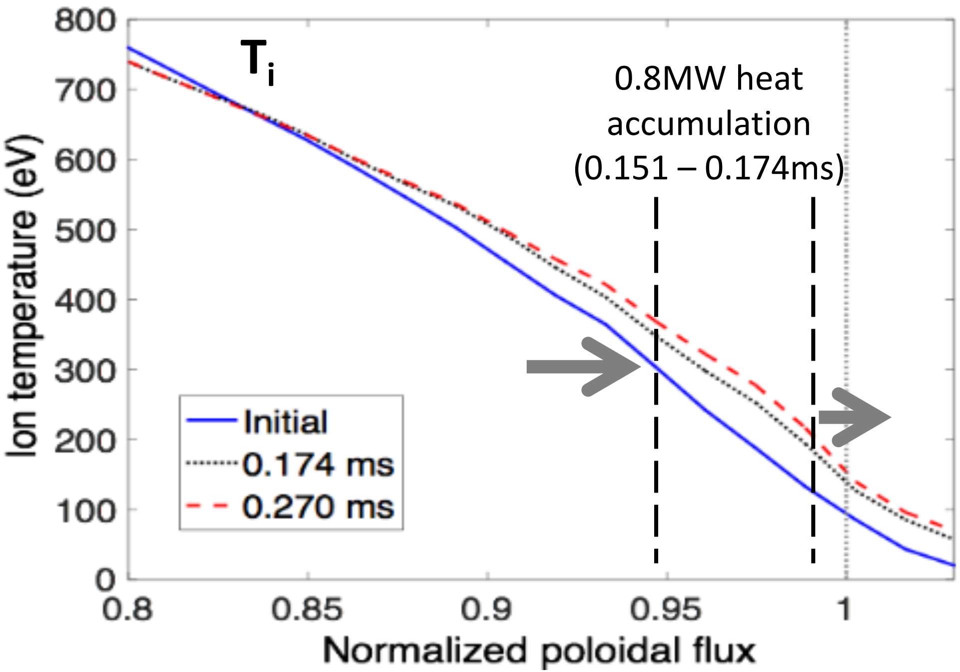
- C-Mod #1140613017 in L-mode, single-null
- $\beta_e \approx 0.01\% < m_e/m_i$ in the bifurcation layer
- $\nabla$B-drift direction has been flipped to be into the divertor

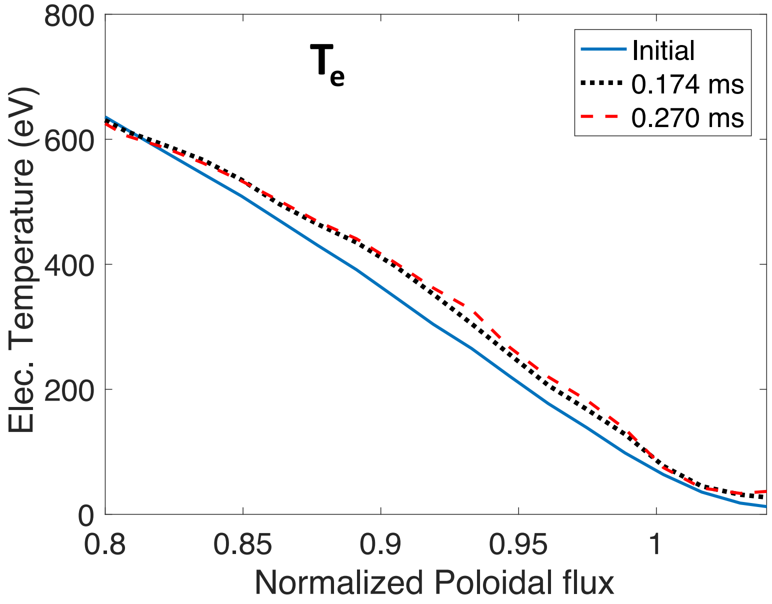
Include the most important multi physics

- Neoclassical kinetic physics
- Nonlinear electrostatic turbulence
- ITG, TEM, Resistive ballooning, Kelvin-Helmholtz, other drift waves
- Neutral particle recycling with CX and ionization
- Realistic diverted geometry

Electromagnetic correction to the present result is left for a future work.

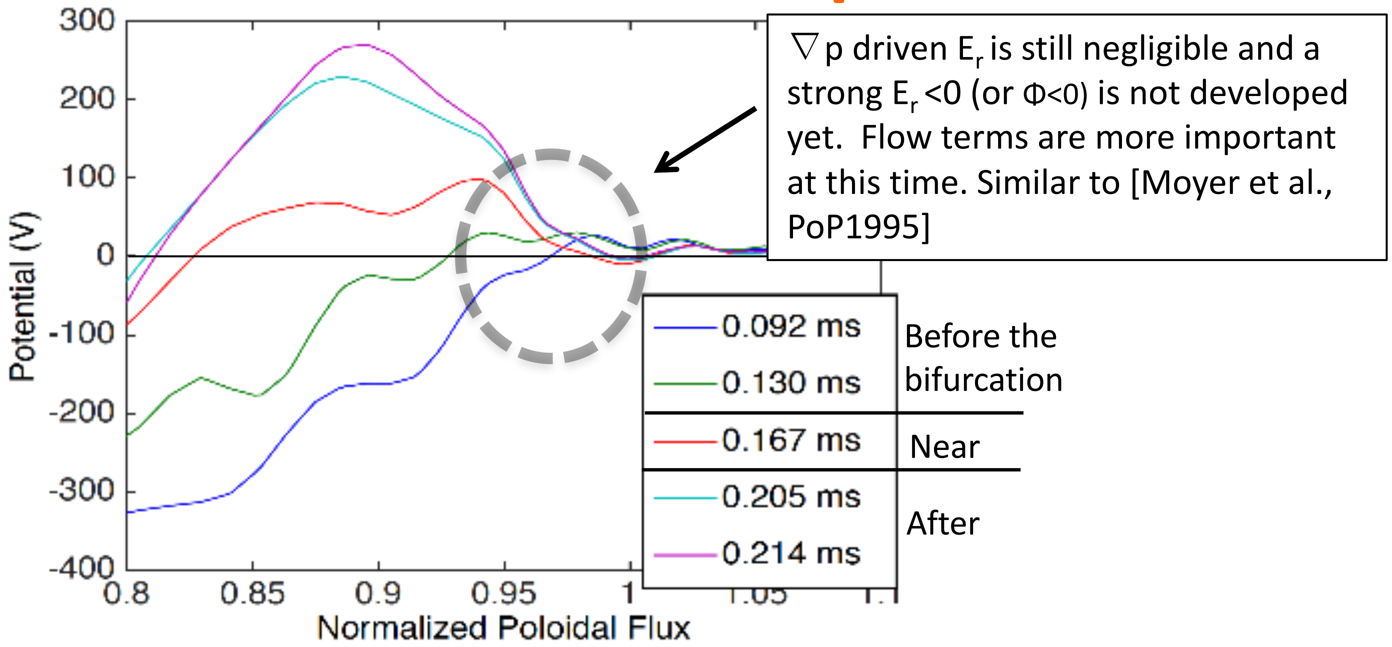
# An L-mode plasma from C-Mod (beta~0.01%)




- Edge temperature increases from heat accumulation
- In a developed H-mode pedestal, $dV_E/dr > 0$ at $\Psi_N$~0.97.Any bifurcation mechanism needs to lead to this sign.

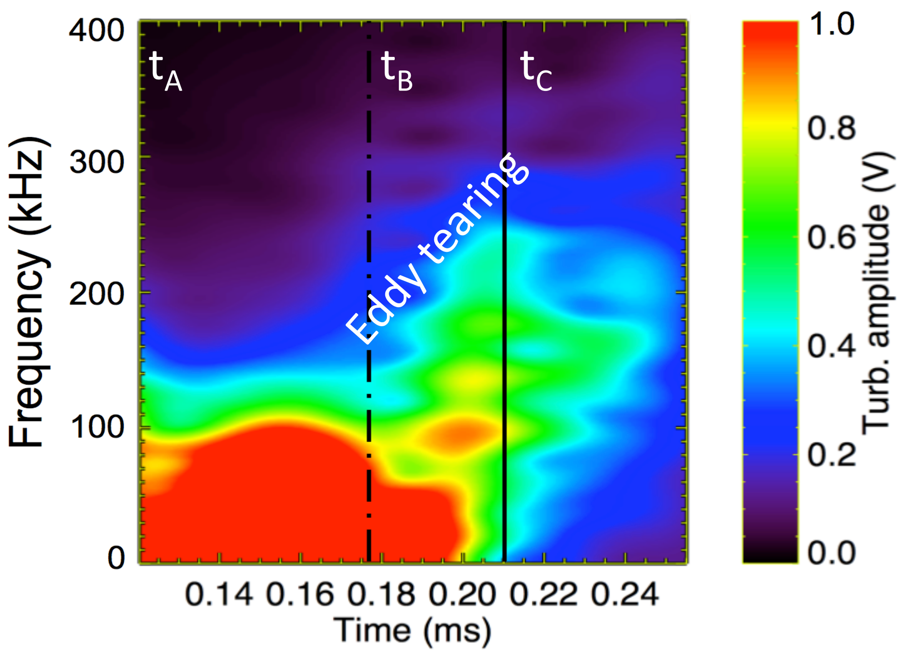
# Electrostatic potential profile measured at outboard midplane




- Transition to significant Φ''>0 (or ρ<0) is a noticeable feature across the turbulence bifurcation time in the edge transition layer, showing a signature of ion X-loss dominant charge loss after the bifurcation.
- **However, Φ is still >0 in most of the edge layer; development of $\nabla$p would yield Φ< 0 and a deeper $E_r$-well.**

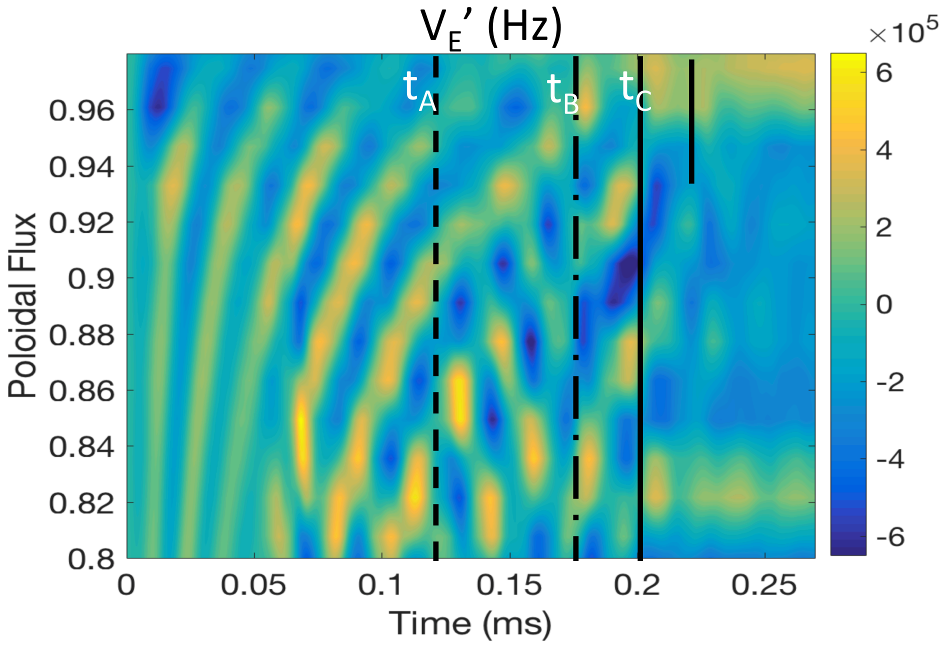
# Overview of the turbulence behavior at bifurcation

1. t~0.175-0.21ms, suppression of lower frequency turbulence occurs, and higher frequency turbulence is generated (shades of green, eddy tearing by ExB shearing, to be shown).
2. t>0.21ms, suppression of all frequency turbulence follows.



# Time-radius behavior of the sheared ExB flow $V_E'$

1. t=0.12ms, $V_E'$ settles down in $\Psi_N$~0.97-98
2. t<0.175ms, $V_E'$ remains negative in the edge layer (ρ>0)
3. t~0.175ms, something pushes the $V_E'$ to be >0 in the edge layer (ρ<0)
4. t >0.2ms, sheared ExB flow locks into the mean ExB shearing in the bifurcation layer.

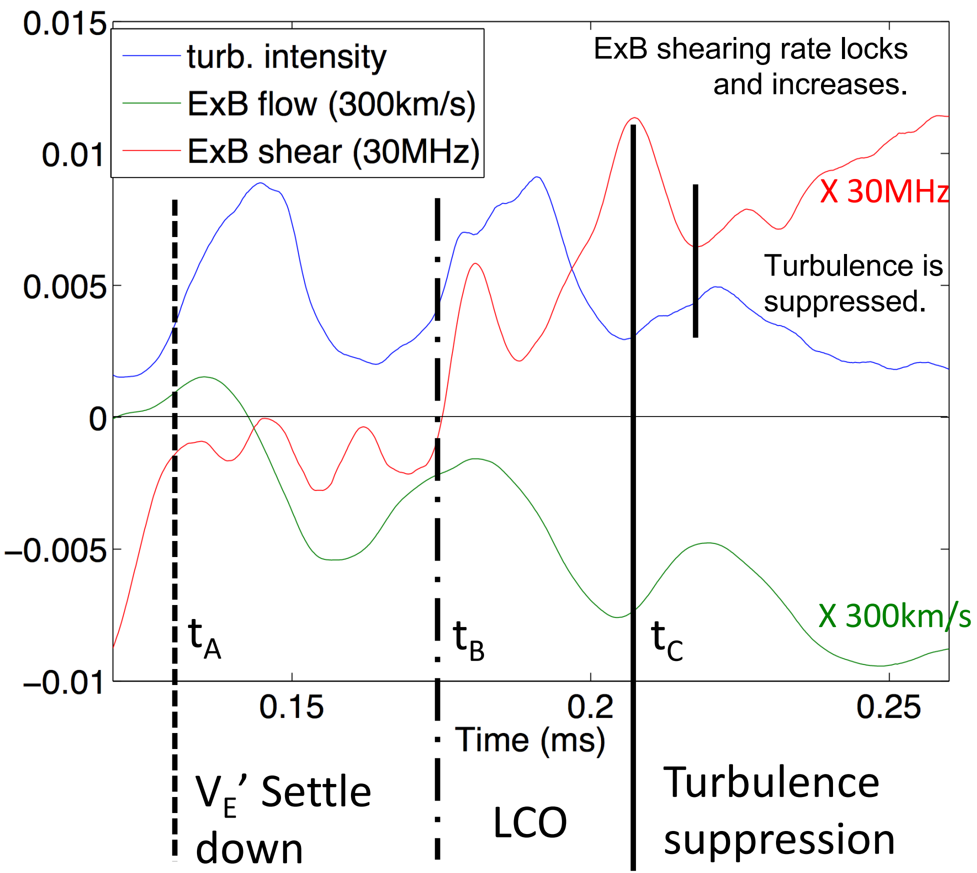



Transition layer is at $0.96<\Psi_N<0.98$, agreeing with C-Mod [Cziegler PPCF2014] and other devices.

[Titan, ALCC 2016]

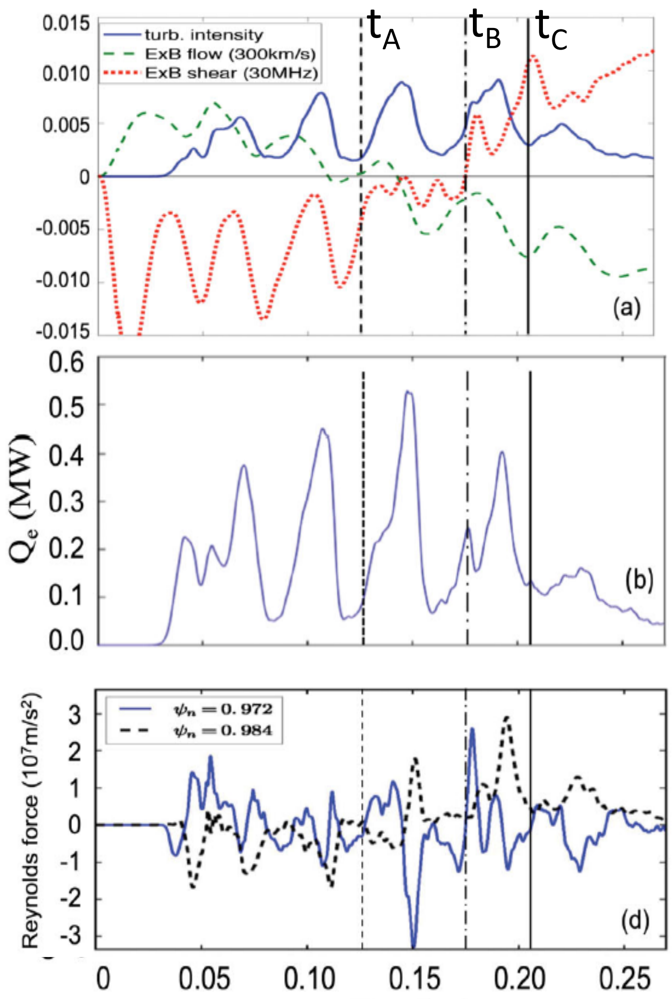
**Detailed local analysis at $\Psi_N$=0.975:**
**(0.96<$\Psi_N$<0.98, per Cziegler PPCF 2014)**

**Important physics quantity is the ExB shearing rate, $V_E'$, not $V_E$.**
**The bifurcation criterion is identified to be $V_E'$ > 300 kHz**
**(Maximum growth rate of dissipative TEMs [Romanelli PoP 2007] ).**



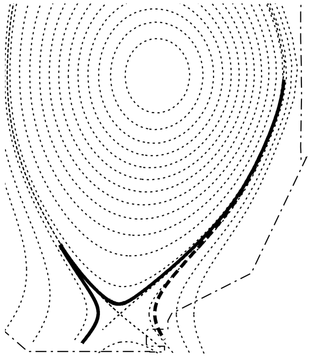
# Transport fluxes and Reynolds force

- Edge transport fluxes are non-local and follow the GAM behavior, with suppression at the “critical” time.
- The Reynolds force from turbulence $F_{\theta,Reynolds}$ = $-d\langle\delta V_r \delta V_\theta\rangle/dr$ fluctuates in both directions, and exhibits shearing
- However, the Reynolds force is a non-player after the bifurcation.
- **Questions:**
  - Why is the negative Reynolds force not effective?
  - What is keeping the turbulence suppressed after the bifurcation?
  - What is pushing $V'_{ExB}$ further to positive after 0.175 ms?
- It is reasonable to conjecture that there is another force in the positive $\mathbf{V_E}'$ direction making the edge plasma more negative.

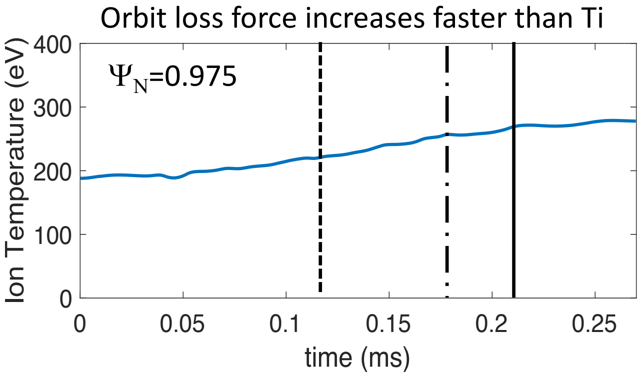


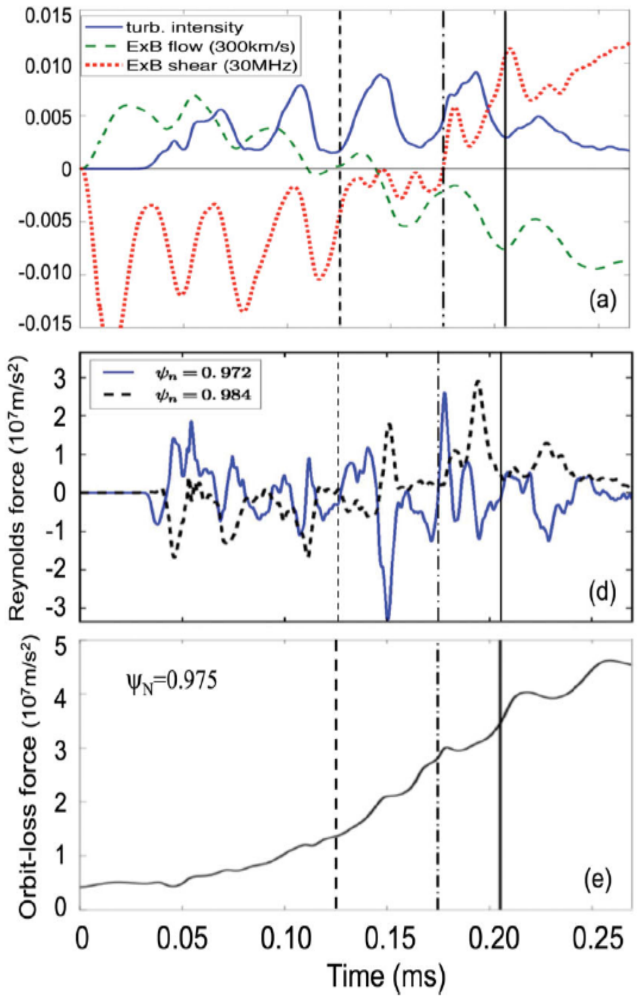
# The X-point orbit-loss physics provides answers to all three questions [Chang PoP 2002]

- **Answers:**
  - The negative Reynolds force is canceled with orbit-loss force and not effective.
  - Orbit-loss force is pushing $V'_{ExB}$ further to positive direction after 0.175 ms.
  - This $V'_{ExB}$ is keeping the turbulence suppressed after the bifurcation.

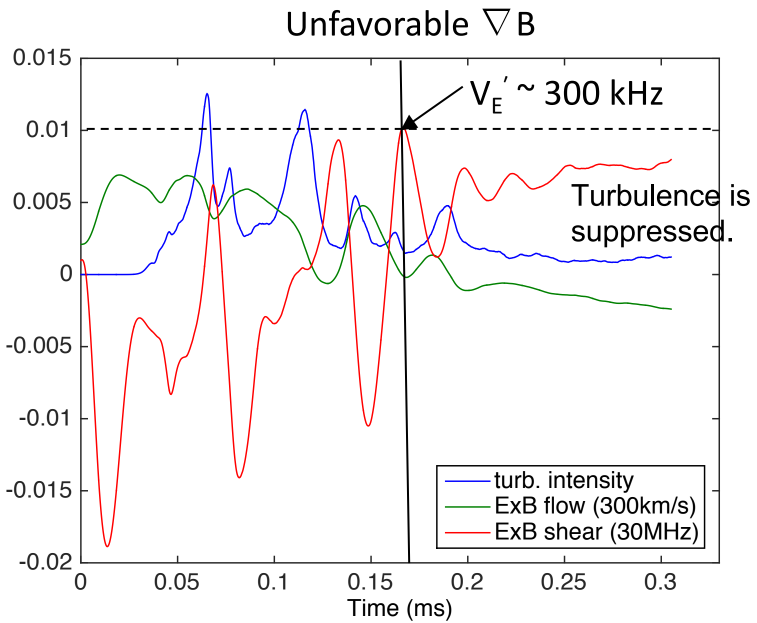


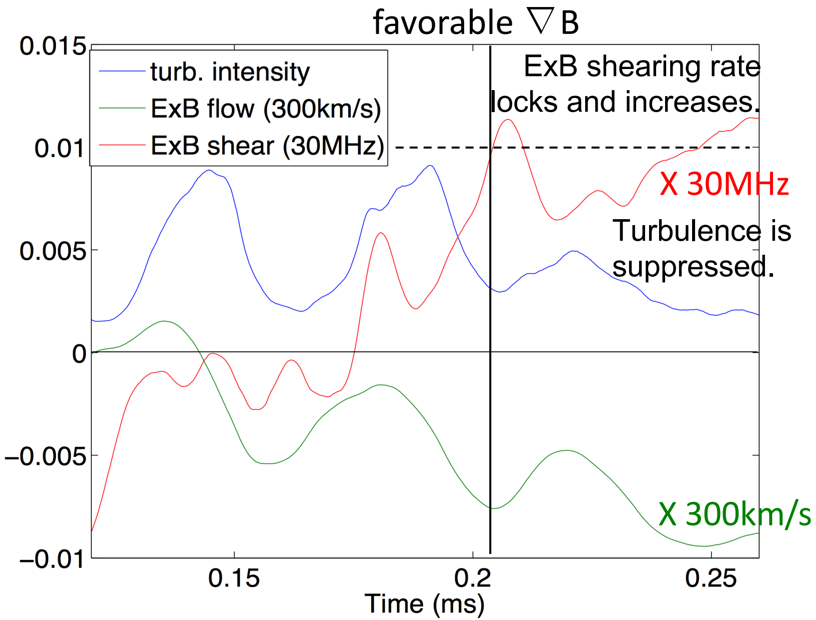
[S. Ku et al., PoP 2004]



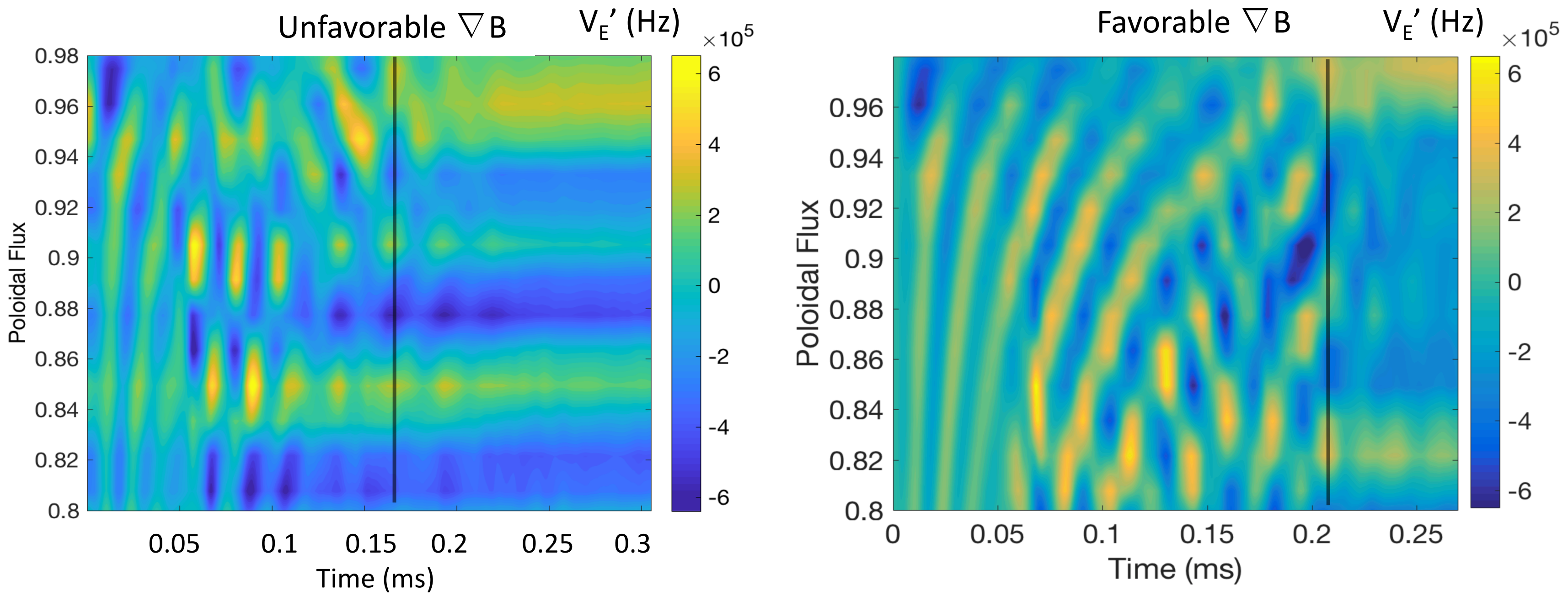
# Unfavorable ∇B drift case is also studied



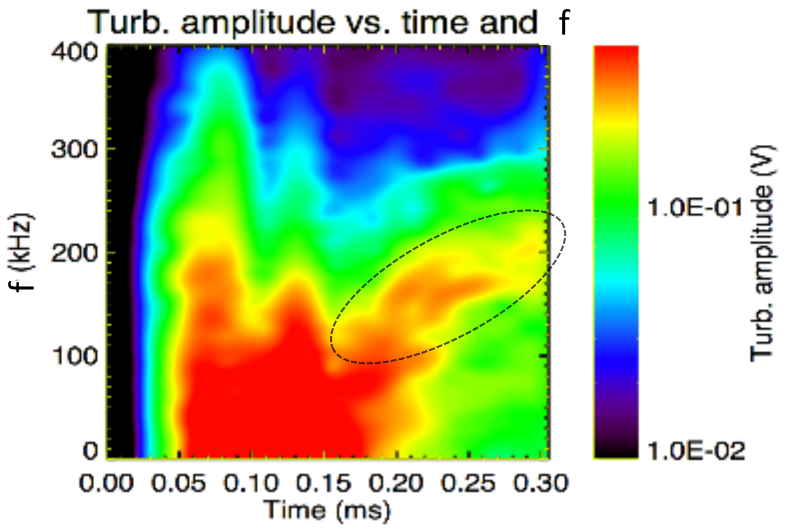

- LCO-type GAM is stronger before the bifurcation.
  - Turbulence energy is getting weaker with strong LCO-type GAM amplitude.
- GAMs persist with the bifurcation.
- The bifurcation criterion ($V_E{}' \sim 300$ kHz) is similar with the favorable ∇B case

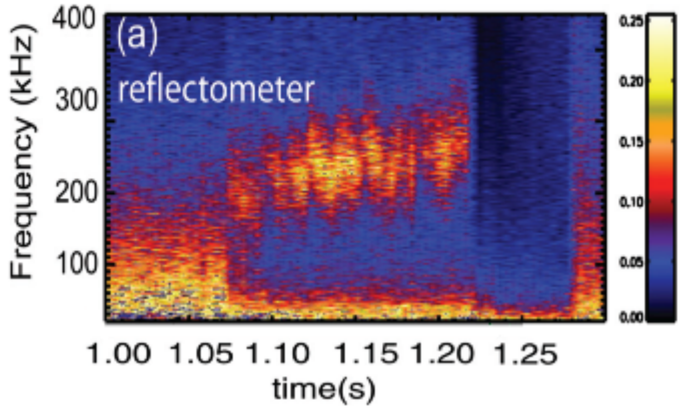
# More robust GAM behavior with unfavorable $\nabla$B




- Locking into background ExB shearing at slightly lower $\psi_n$ position
- GAM is reflected back more strongly at the transition layer
- Stronger standing wave interference pattern in the edge

# Even in electrostatic simulation, weakly coherent modes at high frequency (≳150 kHz) survives with unfavorable ∇B




I-mode [A. Hubbard, PoP 2011]

- Connection to I-mode transition physics is under study

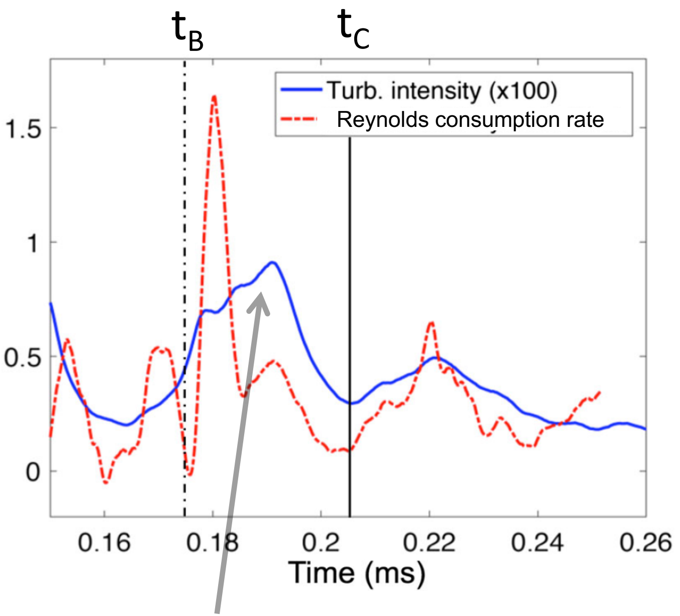
# Summary and Discussions

- A forced, fast L-H like bifurcation physics has been revealed, with transport suppression in both the heat and particle channels.
- The turbulent Reynolds stress and the neoclassical X-loss physics work together in achieving the L-H bifurcation.
  - When combined together, the puzzle pieces appear to come together.
  - How will the geometry and plasma condition change their combination?
  - How will this affect $P_{L\text{-}H}$ in ITER with small $\rho_i/a$?
- Critical ExB shearing rate of unfavorable $\nabla B$ case is the same in the favorable $\nabla B$ case, but GAM LCO is stronger and weakly coherent modes persist through the bifurcation.
- Isotope effects is being studied in DIII-D L-H bifurcation (with G. McKee, L. Smith and Z. Yan).
- EM correction to the present electrostatic result will be studied in the future.

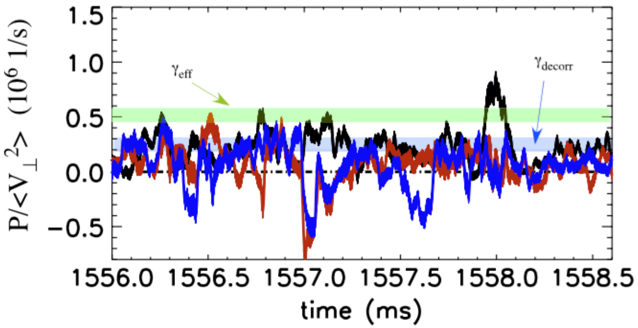
# BACKUP

# Why does the turbulence get cut-off around 0.18ms? What triggers the bifurcation action?

**The normalized, turbulence Reynolds consumption rate $P=\langle\tilde{v}_r\tilde{v}_\theta\rangle V_E' / (\gamma_{eff}\tilde{v}_\perp^2/2)$ becomes >1 in the beginning of the bifurcation action (I-phase), but becomes <1 after that → Zonal flows cannot be responsible for keeping the turbulence suppressed.**




Relevance of the turbulence consumption rate?
Eddie-tearing by ExB shearing could also be responsible for this cut-off.




[Yan PRL 2014] reported a very similar behavior in the Reynolds consumption rate.